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DESIGN DESCRIPTION OF A TENTACLE BASED SCANNING SYSTEM

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Abstract
A design of a tentacle-based 3D object scanning device is presented in this work. The dimensions of the device were 15 ×15×20 cm and a maximum weight of model that can be placed on its platform is 500g. The design requires that two red laser for distance measurement by triangulation be installed on the left and right side of a Charge Coupled Device (CCD) camera. The camera takes the reading as well. The 3D scanner body is made up of polymer matrix for rigidity and dimensional stability. The main mechanism for the scanner is a lead screw and a turntable both managed by National Electrical Manufacturers Association (NEMA) 17 stepper motors.

Keyword: 3D, Scanner, Triangulation, Reverse Engineering, Tentacle

1. Introduction

A three dimension scanner is a device that samples data on the shape and possibly the appearance (i.e. colour) of a real world object. The collected data can then be used to construct digital, three dimensional models useful for a wide variety of applications. For example, these devices are used extensively by the entertainment industry in the production of movies and video games. Other common applications of this technology include industrial design, reverse engineering and prototyping, quality control, inspection and documentation of cultural artefacts (Levoy *et al.*, 2000*;* Lee *et al.*, 2001; Zhang, 2003).

An important part of the three-dimension scanning is data acquisition. Data acquisition systems are constrained by physical considerations from a limited region of an objects' surface. Therefore, multiple scans of the surface are taken so as to completely scan a part.

Technology acquisition and industrial growth does not exist without first copying from existing models, then learning to build on it using available devices and materials. A 3D scanner is a way out in acquiring that knowledge. Most commercial 3D scanners are beyond the reach of many, especially in a developing economy like Nigeria.

Three-dimensional acquisition techniques differs in many aspects, including precision, scanning time and amount of required human interaction. Another central aspect is the categories of objects that can be scanned by complexity and surface properties. Three dimension scanning technology first came into prominence in the early 1990s, where it was used primarily by engineers for reverse engineering purposes (Petrov *et al.*, 1998).

1.1 Technology Used By Scanners

There are a variety of technologies for digitally acquiring the shape of a three dimension object. Scanners use either contact or non-contact technologies. Figure 1 shows a classification of the types of application used for acquiring the three dimensional data.

1.2 Contact 3D Scanners probes the object physically by touching it with a sensing probe – the tentacle. The object needs to be placed on a flat rotating plate. Some objects that cannot keep to a desire posture are normally held in place with a fixture.

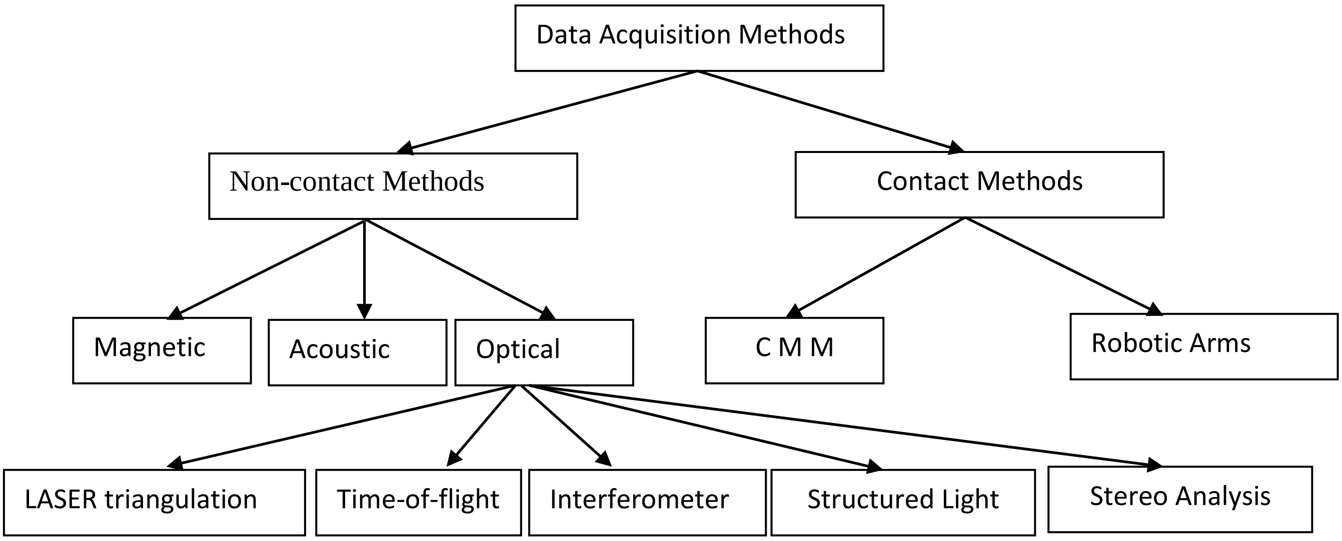

Figure 1: Classification of data acquisition techniques used in contact and non-contact approaches for three dimensional systems.

A coordinate measuring machine (CMM) is an example of a Contact Three Dimension Scanners (CTDSs). It is mostly used in manufacturing and can be very precise. The sample is usually placed on the machine while the scanner or robotic arm goes round the sample while taking measurements. It is usually advised to use this setup when the sample surface is hard and is not flexible. However, there are disadvantages using a contact three dimension scanner for delicate objects, even with hard surfaces because of their delicate finishing or parts which may be damaged if their issues like vibration. Also CMM has the problem of modifying or damaging the object in contact with it during scanning process, especially when the material in contact with it has a soft texture. If the part that is being scanned has indentions that are too small for the probe head of the scanner, it will lead to inaccurate scan. CMMs are also relatively slow compared to other scanning methods. Physically moving the probe around the object being scanned is slow due to inertia. In contrast, an optical system like a Laser scanner can operate at up to 500 kHz (Faxin *et al.* 2010). There are also external factors that affect the accuracy of a CMM which include temperature, vibration and humidity. Other examples of (CTDSs) are the hand driven touch probes used to digitize clay models in computer animation industry (Faxin *et al.* 2010).

1.3 Non-contact 3D scanners

These can be further divided into two main categories, namely active and passive scanners. There are a variety of technologies that fall under each of these categories. Apparently, the process of contact scanning might modify or damage the scanned object of which the consequence is very significant when scanning delicate or valuable objects. Each method has strengths and weaknesses that require the data acquisition system to be carefully selected for the shape capture functionality desired. Non-contact methods use light, sound, or magnetic fields to acquire shape from objects. In the case of non-contact methods, an appropriate analysis must be performed to determine the positions of the points on the objects surface. A brief description of each method is presented as follows:

1.3.1 Magnetic Field Method: This method refers to Magnetic resonance imaging (MRI) and is good for scanning soft tissues (Ares *et al*., 2014).

1.3.2 Acoustic Method: This method uses high frequency sonar source to measure the object surface depth. It has an inherent problem of being unable to discriminate features (Tardos *et al*., 2002) as well as specula reflection (Deniz and Billur, 1999).

1.3.3 Optical Methods: This method includes the following:

a. Laser Triangulation: Using LASER light to perform the scanning and depth of surface measurement.
b. Time-of-Flight: The time-of-flight 3D uses method similar to that of acoustic scanner but using light source for the probing action.
c. Interferometers: Using optical interferometer to measure surface distortion at a distance. The optical source is a monochromatic light source like LASER.
d. Structured lighting: This method involves the projection of a known pattern onto the object being scanned. Another device such as camera record and analyze the pattern deformation and use it to reconstruct its 3D.

1.4 General Constraints of Data Acquisition Techniques with Non-contacting Methods

There are many practical problems with acquiring useable data (Bardell *et al.*, 2003; Beraldin *et al.*, 2003), the major constraints are:

a. ***Calibration requirements****:* Systematic sensing errors can occur through lens distortions, non-linear electronics in cameras, and similar sources. Any sensing must be calibrated so as to firstly, accurately determine parameters such as camera points and orientations, and secondly, to model and allow for as accurately as possible systematic sources of error.
b. ***Occlusion****:* This is the blocking of the scanning medium due to shadowing or obstruction of the rays by raised or sunken parts – see figure 2. This is primarily a problem with optical scanners. However, acoustic and magnetic scanners may also have this problem.

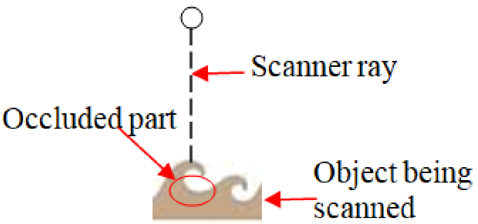

Figure 2 Parts occlusion during ray tracing

c. ***Multiple views:*** Error due to multiple views is introduced when acquired data has a registration problem; that is, the final result is a stitch of two or more scans (often oversized objects broken into pieces) and the result has problems of non-matching edges from consecutive scans intended to be stitched together.
d. ***Noise***: Noise can be introduced in a multitude of ways, from extraneous vibrations and specula reflections as the two common sources.

1.5 Justification for this Study

As a developing nation, Nigeria scientist needs to acquire and copy other existing technologies. The copying process is faster if the object can be captured in three-dimension (3D) and printed on a 3D printer. The scanning devices are often very expensive ($9,800 - $39,800; https://www.artec3d.com/shop) and are often beyond the reach of many would be researchers, except government sponsored. A single station (or booth) of high resolution 3D capturing center can have more than 40 high grade SLR cameras (single-lens reflex cameras) with each costing several thousand US dollar.

1.6 Objective of the work

The objective of this work is to present a design of a tentacle based scanning system which can be used for scanning objects with a dimension of 150mm (maximum length), width of 150mm, height of 200mm and weight of 500g (0.5kg). A tentacle based scanner measure the relative depth or height of points on an objects being scanned and stored this information in a preferred 3D file formats such as stl and 3xg.

2.0 Materials and Methods

2.1 Design Considerations

The following were put into consideration in the design of the 3D scanner:

1. Material: The consideration of the entire system includes the availability of the material, machinability, weight, size, mechanical properties and the environment in which the machine will be used.
2. Compact design: The machine was designed to be portable (not requiring much space), easy to operate and safe.
3. Cost of design and construction: This accounts for the cost incurred in the design and construction of the scanner.
4. Flexibility: The scanner was designed to be rigid and fixed such that it does not bend during any scanning process and devoid of noise error.

2.2 Description of the Scanner System:

The scanner structure (Figure 3) consists of the following:

1. The frame, comprising of a horizontal platform and a vertical standing frame
2. The rotating mechanism, this includes the turntable, a stepper motor
3. The capturing devices, which includes the camera and two red lasers.

2.3 Working Principles of the Scanner

An object to be scanned would be placed on the turntable component and then rotated from angle 0° through to 360° by the stepper motor; so that all the sides of the object are scanned completely. A camera and two lasers attached to a power screw are placed on the vertical standing frame. The camera and lasers move up and down as the power screw is rotated. As the camera and lasers move up and down, the distance between the object and the camera is measured. The camera and Lasers assembly move a specified distance for each revolution of the turntable.

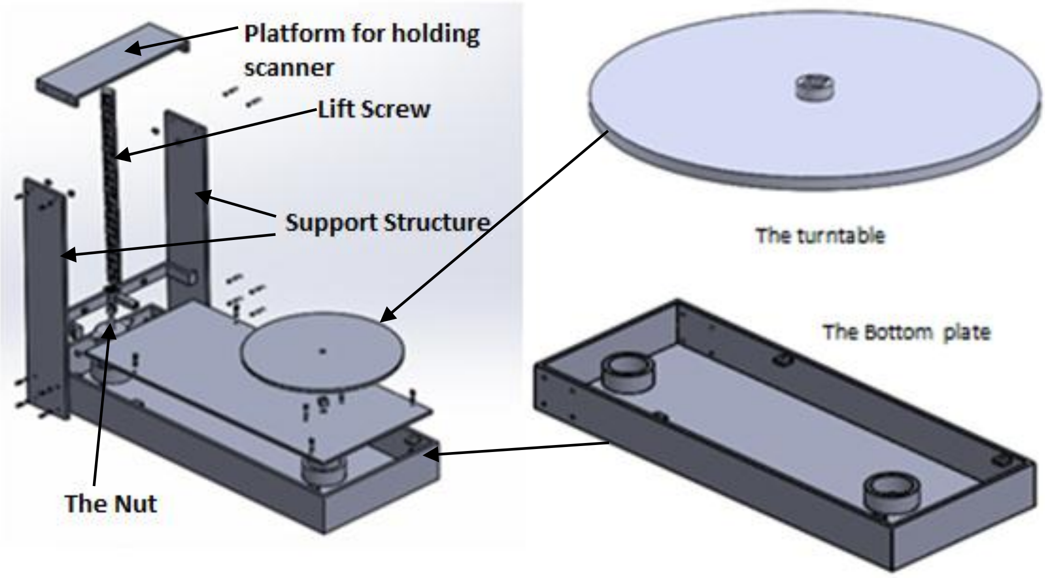

Figure 3: Exploded view of the scanner.

2.4 Construction Materials

Polymer composite matrix material is to be used for the construction of the frame so as to achieve a dimensionally stable structure that would not introduce errors during the scan process. Other reasons for considering the polymer matrix are its mechanical stability, low cost, good workability, high rigidity, light weight and has a good corrosion resistance. Other materials are:

i. The frame – this will be made up of 4mm to 5mm-thick sheet of polymer composite matrix for the horizontal base and the vertical beam
ii. Two National Electrical Manufacturers Association (NEMA) 17 stepper electric motors; one for the lift screw and the other for the turntable
iii. An STL-6303E charge-coupled device (CCD) camera
iv. 2 Class-1 red line Diode lasers
v. Lift Screw (a threaded rod – 250mm long, 4mm thread pitch, mean diameter of Ø10mm, outer diameter of Ø12mm
vi. Rotating turntable
vii. Assembly Screws

2.5 Design Theory of Some Mechanical Components of the Scanner System

The lift screw is fixed to the electric motor at the vertical end of the scanner system. The stepper motor will rotate the power screw in a clockwise and anti-clockwise directions. A nut is attached to the power screw which holds the platform for supporting the camera and laser diodes. The nut is fixed such that it does not rotate, but as the lift screw is rotated either clockwise or anti-wise direction, the nut moves up or down. The following mechanical behavious will be experienced while in operation:

i. Torque required to raise load by the lift screw (Khurmi and Gupta, 2005) (see figure 3)

$$T = P \times \frac{d}{2} = W \tan(\alpha + \phi)\frac{d}{2} = W\left(\frac{\tan\alpha + \tan\phi}{1 - \tan\alpha\tan\phi}\right)\frac{d}{2} \quad (1)$$

ii. Torque required to lower load by the lift screw (Khurmi and Gupta, 2005) (see figure 3)

$$T = P \times \frac{d}{2} = W \tan(\alpha - \phi)\frac{d}{2} = W\left(\frac{\tan\alpha - \tan\phi}{1 + \tan\alpha\tan\phi}\right)\frac{d}{2} \quad (2)$$

where: P = Effort applied at the circumference of the lift screw (N),
W = Load to be lifted (N),
d = Mean diameter of the screw (mm),
ϕ = is the friction angle (rad),
α = Helix angle (rad),
μ = coefficient of friction of screw = tan ϕ.
p = thread pitch (mm)
$\tan\alpha = \frac{p}{\pi \times d} = 0.127$

iii. Torque required to overcome static friction (between the screw and the nut)

$$T = P \times \frac{d}{2} + \mu W R$$

Where $R = \frac{R_1 + R_2}{2}$ = average radius of the screw collar
R_1 = inner radius

R_2 =outer radius

iv. Shear stress within the lift screw (Khurmi and Gupta, 2005) (see figure 3)

$$\tau_{(screw)} = \frac{W}{\pi \times d_c \times t \times n} \tag{3}$$

v. Shear stress on the nut (Khurmi and Gupta, 2005) (see figure 3)

$$\tau_{(nut)} = \frac{W}{\pi \times d_o \times t \times n} \tag{4}$$

where: $\tau_{(screw)}$ = Shear stress in screw,
$\tau_{(nut)}$ = Shear stress of nut,
W = Axial load on screw (N),
n = Number of threads in engagement between them,
t = Thickness or width of the screw thread (m),
d_c = Core or root diameter of screw (m),
d_o = Major/ outer diameter (m)

vi. Efficiency of the lift screw-nut assembly

$$\frac{\tan \alpha}{\tan(\alpha+\phi)} \tag{5}$$

The following specification are intended for the lift screw and the nut; pitch (p) of the screw thread = 4mm and mean diameter (d) = 10mm, maximum diameter (d_o) = 12mm, coefficient of friction, between the screw and nut, μ = 0.15 (assumed value from Khurmi and Gupta, 2005). Number of threads in engagement between the screw and the nut at any time (n) = 8, screw thread thickness (t) = 2mm.

2.6 Description of the Scanner Components

The scanner is a mix of a sensor made up of a Charge Coupled Device (CCD) camera and two point light sources to be made up of 2 light emitting diodes (LED) based red Laser.

2.6.1 The CCD Camera

The sensory system will use a CCD camera. This camera will be equipped with lenses for focusing. The lenses design will have the possibility of being locked to reduce needs for regular calibration process. The camera would be placed in the middle of the two lasers to enhance the systems resistance to occlusion effects.

2.6.2 The Laser

Two red line lasers will be attached to the left and right side of the CCD camera for distance measurement using triangulation. As the turntable rotates (figure 3), the laser is pulsed while the camera performs the data capturing. At the end of each measurement, the depth data, that is, the distance of the point under focus on the image to the CCD camera plane, can be calculated using lens law. The lens law (equation 6) implies that to get a well-focused image on the CCD camera plane, the relations must be obeyed.

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s°} \qquad \text{(Nave, 2018)} \qquad (6)$$

where: f = the focal length (m), s = distance of the object (m), s° = is the optical image distance where the theoretical sharpest image is formed (m).

2.6.3 Stepper Motor

A stepper motor is recommended for this design; other motors such as servo motors are equally suitable. The National Electrical Manufacturers Association (NEMA) NEMA17 stepper-motor is recommended because of its popularity. It is commonly used in household appliances, medical equipment, stage lighting devices, and in various industrial control applications. It has $0.15m^2$ footprint, 5 mm shaft diameter and uses 12 V input voltage. This motor, like most stepper motors is a permanent magnet motor. It has high resolution– a full revolution requires 200 steps, while each step turns the shaft only 1.8° for a full step, or 0.9° in half-stepping mode. Mosaic (2006).

2.6.4 Bolts and Nuts

The bolts and nuts are used for fastening the scanner parts together for easy assembling and dismantling. They were chosen due to their availability, easy maintenance and low cost.

3 Result and Discussion

The maximum load W, (the camera and laser) to be raised by the platform (figure 3) is estimated to be 2.5 kg using STL-6303E specification – SBIG (2011). Using the design specification and equations from section 2.4, the following results are obtained;

i. Torque that will be required to raise the camera and laser by the lift screw is 3.53N-mm
ii. Torque that will be required to lower the camera and laser by the lift screw is -0.28N-mm
iii. Torque required to overcome friction between the screw and the nut – platform is fixed to the nut and does not rotate is 30N-mm

Thus the total torque required to raise the load is 33.53 N-mm (3.53 + 30 N-mm) and the torque to lower the load will be -30.28N-mm (-0.28-30) – it is additive since friction opposes motion.

iv. Shear stress that will be experienced by the lift screw is 6.22×10^{-3} N/mm^2
v. Shear stress that will be experienced by the nut 4.14×10^{-3} N/mm^2
vi. Efficiency of the lift screw-nut assembly is ~45%

For implementing the lift screw and nut, engineering plastics such as polyacetal and Nylon which is essentially polyamid resin could have served because plastic materials are lightweight, non-rusting, quiet, and can be injection molded enabling low cost and large production, and they can operate without need for lubrication. The discouraging aspect of these materials is basically the lack of dimensional stability. The scanning operation requires very stable dimension and high precision in the face of fluctuating environmental temperature.

An alternative material known for good dimensional stability is cast iron. There are four basic types of cast iron (white iron, gray iron, ductile iron, malleable iron) each with its own merits. White Cast Iron is recommended for the lift screw and its nut because of its high compressive strength, hardness, good resistance to wear etc (due to the presense of carbide in its microstructure).

The cost of implementing the designed scanner can be estimated as shown in Table 1. This cost excludes the development of the firmware which is a major research work on its own.

Table 1: Cost estimate of the scanner construction material[1]

S/No	Description	Quantity	Unit price in Naira	Total price in Naira	Remark
1	Nema 17 electric motor	2	5,500:00	11,000:00	
2	Laser light	2	550:00	1,100:00	
3	Lead screw and round nut	1	1,000:00	1,000:00	Estimate
4	Frame (fabricated)	1	5,000:00	5,000:00	Estimate
5	Camera	1	8,500:00	8,500:00	
6	Screws	20	20:00	400:00	
7	Power source (regulated)	1	2,500:00	2,500:00	
8	Arduino - Arduino UNO R3	1	4,500:00	4,500:00	
9	Miscellanous			5,000:00	
	Total			39,000:00	

[1] The other aspect is the firmware to run in the microcontroller.

4. Conclusion and Recommendation

This work presents a design of 3D scanner that should be able to hand an object with frame volume of 150mm x 150mm x 200mm. A dual Laser diode is incoporated into its design so as to eliminate occlusion. The Laser diodes acts as the tentacle. They in conjuction with the CCD camera, measures the distances between the surfaces of the object being scanned and themselves (through triangulation) and save this information as the 3D data of the object.

The firmware (the brain) of the system is hereby recommended for others to developed. The firmware design is a major work on its own and its implementation will determine how well the scanner will perform in real situations.

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